Asantha Cooray[1] and Alessandro Melchiorri[2]

[1] *Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125. E-mail: asante@caltech.edu*

[2] *Theoretical Astrophysics, University of Oxford, Oxford, OX 3RH. E-mail:melch@astro.ox.ac.uk*

The advent of high resolution cosmic microwave background (CMB) experiments now allow studies on the temperature fluctuations at small angular scales corresponding to few arcminutes. At these angular scales, temperature anisotropies are generated by effects related to the local universe, through effects such as scattering of CMB photons via free electrons. Another strong possibility for anisotropies at these scales involve non-standard aspects of inflationary models. To distinguish between contributions from early universe and local structures and to understand the extent to which structures at low redshifts contribute to small scale temperature anisotropies, it may be necessary to perform a combined study involving CMB and the large scale structure. We suggest a cross-correlation of the temperature data with a map of the large scale structure, such as the galaxy distribution. For next generation small angular scale CMB experiments, multi-frequency observations may be a necessary aspect to allow an additional possibility to distinguish between these different scenarios.

The advent of high resolution, and high signal-to-noise, cosmic microwave background (CMB) experiments like Boomerang ([1]), DASI ([2]) and MAXIMA ([3]), has opened the study of temperature anisotropies at arcminute scales and below.

In the near future, we expect anisotropy results related to such angular scales from experiments such as the Cosmic Background Imager (CBI; [4]), the Arcminute Cosmology Bolometer Array Receiver (ACBAR), which completed a season of observations from the South Pole, and the BIMA array outfitted with centimeter-wave receivers [5]. The presence of anisotropies at such angular scales are both well known and expected.

In addition to the primary anisotropy contribution at the recombination, on transit to us, CMB photons are affected by the large scale structure of the universe. This leads to modifications in the temperature anisotropy structure including a regeneration of new temperature fluctuations. These modifications come effectively from two process involving gravity and scattering. A well-known effect related to gravity is the imprint of frequency variations when photons fall in and climb out of time-varying potential perturbations. This integrated Sachs-Wolfe effect (ISW; [6]) contributes primarily at large angular scales. An important contribution at small angular scales due to gravity is the lensing effect. The gravitational lensing of CMB photons by the intervening large-scale structure both redistributes power in multipole space and enhances the power in the damping tail via the small scale density perturbations [7].

The inverse-Compton scattering of CMB photons via hot electrons, the Sunyave-Zel'dovich effect (SZ; [8]), produces a now well-known contribution at angular scales corresponding to projected galaxy clusters extents of order few arcminutes and below. The SZ effect has now been directly imaged towards massive galaxy clusters [9], where temperature of the scattering medium can reach as high as 10 keV producing temperature changes in the CMB of order 1 mK at Rayleigh-Jeans (RJ) wavelengths and whose presence is a priori known based on optical data. These, and other unresolved, clusters contribute to the dominant anisotropy contribution at arcminute scales. In figure 1, we show the power spectrum associated with the SZ effect calculated following the techniques described in [10,11]. Similar results have been presented in [14]. Additional contributions at these small scales also include the kinetic SZ effect, or the non-linear Ostriker-Vishniac effect [12], associated with the peculiar motion of galaxy clusters and a contribution resulting from the patchy, or inhomogeneous, reionization [13]. The latter effect is the modulation of the first-order Doppler contribution by the fraction of ionized electrons, while the former effect is the same modulation, but with the density fluctuations captured by galaxy clusters containing electrons. In general, these scattering effects, and effects related to gravity mentioned before, are generally lower than the thermal SZ contribution. We refer the reader to Ref. [15] for a discussion of these contributions and their importance for understanding the large scale structure via CMB anisotropy observations at small angular scales.

In addition to a contribution from the large scale structure associated with the local universe, it is also possible that there is an extra contribution to temperature anisotropies at small angular scales in non-standard models of inflation. A strong possibility, for example, that has recently been discussed in detail is the existence of primordial voids in the early universe* [16–18]. There is an important contribution from these voids to temperature anisotropies. Similar to the Sachs-Wolfe (SW; [6]) effect associated with the dark matter potential at

*For the purpose of this discussion, note that we define early universe to be the era around, and before, recombination ($z \sim 1000$), while the local universe is the era after reionization ($z \lesssim 10$).

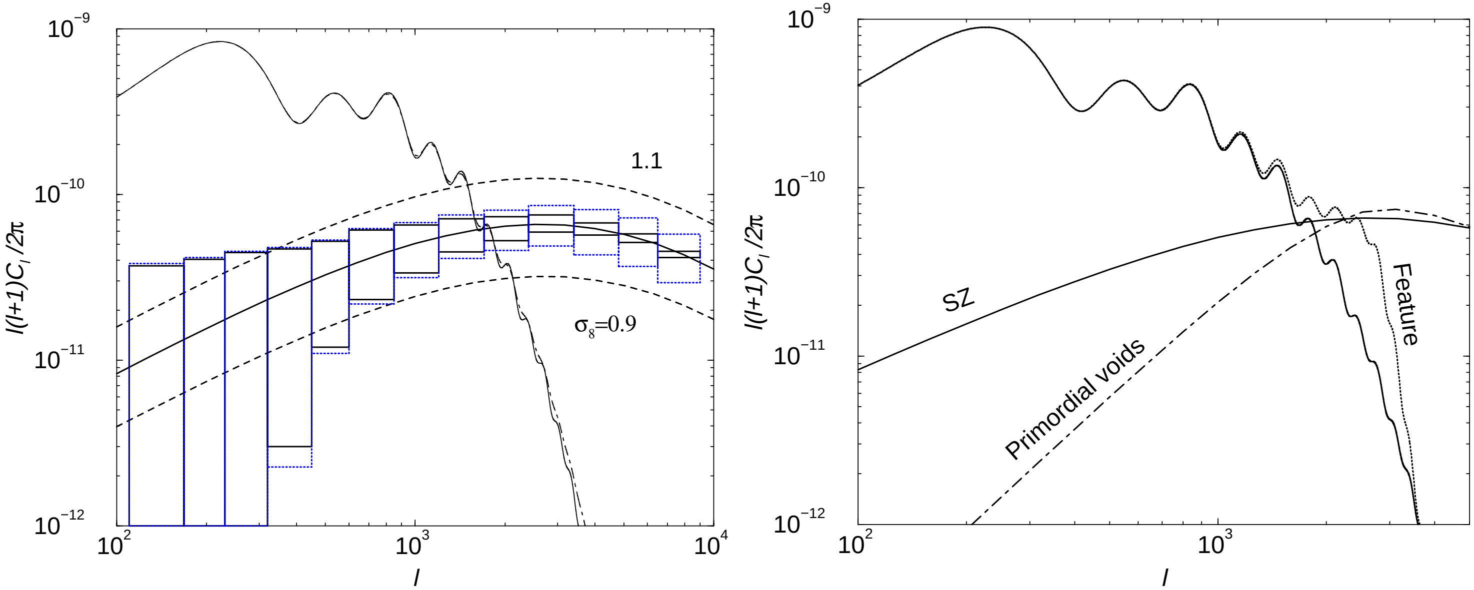

FIG. 1. *Left:* The thermal SZ power spectrum. The three curves show the variation in the SZ contribution due to a change in the normalization about $\sigma_8 = 1.0$. Due to the highly non-linear behaviour, the SZ thermal contribution is strongly dependent on the normalization of the matter power spectrum. The two sets of error bars show the highly non-Gaussian behaviour of the clusters that contribute: the small error bars in solid are the ones expected under a Gaussian description, while the dotted errors bars show the total errors including the covariance due to non-Gaussianities. For illustration, we have assumed a no instrumental noise survey of 1 sqr. degrees. In addition to increasing the errors by a factor of a few, non-Gaussianities also correlate the arcminute scale band power estimates at the 50% to 90% level. *Right:* Possible contributions to small scale power from effects related to the early universe. These include a contribution froma feature in the primordial spectrum of fluctuations (dotted line), a distribution of primordial voids at the last scattering surface (dot-dashed line). For comparison, we also show the SZ contribution and the standard prediction for anisotropy power spectrum.

the last scattering surface, these primordial voids also generate a SW contribution. The angular scale for this latter SW temperature fluctuations are consistent with the projected size of the void at the last scattering surface. Note that voids which are fully embedded in the primordial photon-baryon fluid do not generate a new anisotropy contribution via the SW effect.

Following the discussion presented in Ref. [17], for illustration purposes, we calculate the SW contribution associated with voids using parameters which are consistent with voids observed via redshift surveys of the present day and a volume fraction, again, consistent with such observations [19]. More detailed and accurate numerical predictions have recently been presented in [18] and are beyond the scope of the present work. Between the last scattering surface and today, these voids also contribute to additional temperature anisotropies through frequency shifts, mainly the Rees-Sciama effect (RS; [20]) and effects such as gravitational lensing.

Another possibility, recently investigated by various authors (see e.g. [21]) but in different contexts, is the presence of a feature in the primordial spectrum of fluctuations, as expected, for example, in inflationary models with broken scale invariance. In Fig.1 we present the possible contribution to the small scale anisotropies from a feature in the spectrum modeled as gaussian centered at $k \sim 0.20[hMpc^{-}1]$ with dispersion $\Delta k \sim 0.03[hMpc^{-}1]$ and amplitude $A \sim 5$. While this feature is not fully ruled out by results on the matter power spectrum from recent galaxy redshift surveys such as the 2dF (see e.g. [22]), its width is still dangerously close to the observed spectral resolution around these scales. Though models involving primordial features only produce excess power over a limited range in multipolar space, in this case, only out to a $l \sim 3000$, the current small scale anisotropy observations are also limited in the coverage of the power spectrum complicating any identification of a feature. In addition to all these possible contributions arising from modifications to the standard inflationary scenario, we also note that there may be additional possibilities to generate small scale anisotropies at the last scattering via modifications to recombination [23].

Given distinct possibilities for small scale temperature anisotropies, involving the large scale structure after reionization and the last scattering surface, an important question is how to distinguish between them when interpreting any detection of power at smaller angular scales in current and future experiments. For the purpose of this discussion, we will assume that the main contributor at small scales due to large scale structure is the SZ effect. This assumption is certainly consistent with both analytical and numerical expectations [15]. A useful aspect related to the SZ contribution is its distinct frequency dependence. This spectrum can be utilized to

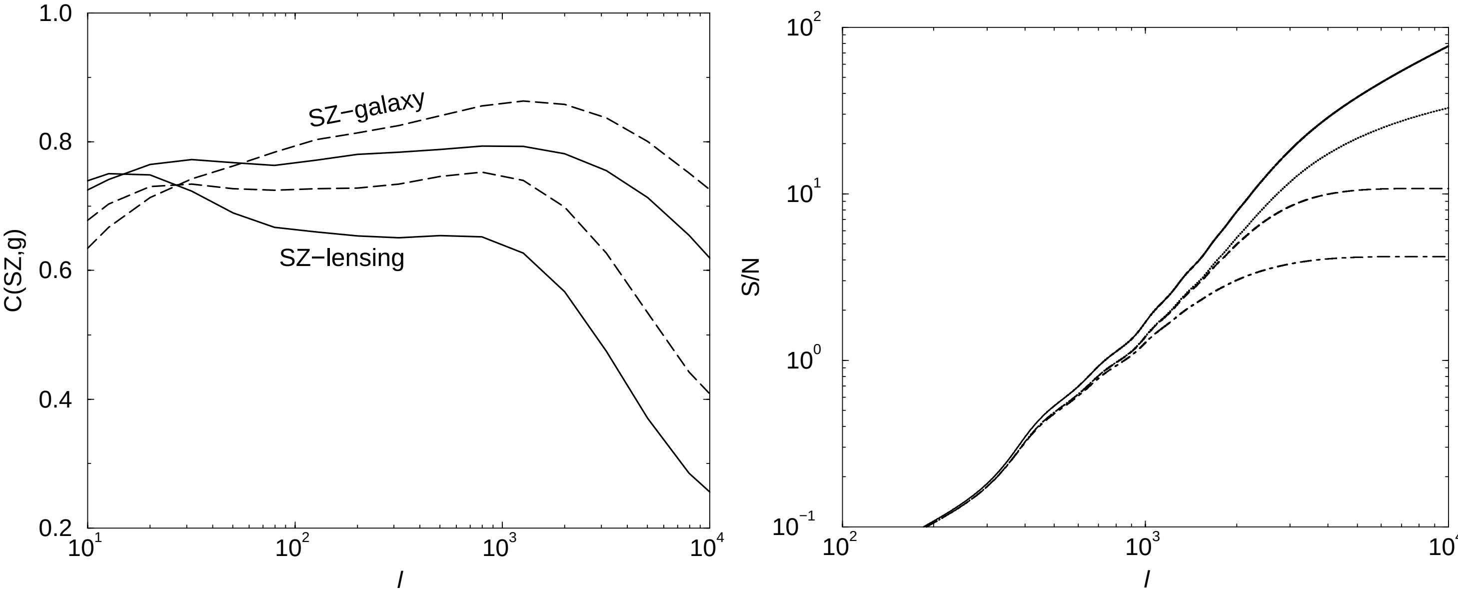

FIG. 2. *Left:* The SZ-large scale structure correlation coefficients. The curves are for large scale structure tracers involving galaxies, with a median redshift of 0.5 (dashed bottom) and 1.0 (dashed top) and weak lensing, with background sources at redshifts of 1.0 (solid bottom) and 3.0 (solid top). In general, large scale structure tracers are correlated with the SZ effect at arcminute scales with correlation coefficients of order ~ 0.6, when median redshift involved is of order 1. *Right:* The cumulative signal-to-noise ratio for the detection of SZ-galaxy cross-correlation. We assume a survey of 10 degrees^2 and a year of observations. The solid line is the maximum with no instrumental noise or shot-noise contribution, while the dotted line is the signal-to-noise ratio with a galaxy surface density of 10^9 sr^{-1}, the dashed line is the signal-to-noise ratio with an additional instrumental noise for the small scale CMB experiment with a sensitivity of 25 μK $\sqrt{\rm sec}$ and a beam of 2 arcmins (FWHM) and the dot-dashed line is the ratio when the sensitivity is 100 μK $\sqrt{\rm sec}$.

separate its contribution from the dominant anisotropies associated with primary fluctuations at large scale and other thermal fluctuations, such as due to the SZ kinetic effects associated with the peculiar motions of clusters, as well as any void or non-standard contribution, at small angular scales [24]. The current anisotropy observations at small scales, unfortunately, are limited at most to a single frequency and this limitation is unlikely to be improved significantly till the advent of next generation of experiments. In the case of CBI and BIMA, observations are limited to 30 GHz at the RJ part of the spectrum. We expect observations, at higher frequencies, such as at 150 GHz by the ACBAR instrument to see a contribution which is lower than at 30 GHz, by a factor of ~ 0.22, though, observations at and above the SZ null frequency of 217 GHz are clearly desirable.

An additional aspect of the SZ effect is its non-Gaussianity. It is now well established that contributions to the SZ effect primarily comes from massive galaxy clusters which are rare. Such a mass dependance makes the SZ effect highly non-linear. As illustrated in figure 1, for example, the SZ effect varies by a factor of ~ 2 when the normalization of the matter power spectrum is changed by $\sim 10\%$. Another aspect of this non linearity is the increase in SZ variance when compared to the expected Gaussian variance contribution. We discussed the full-covariance, including the non-Gaussian contribution, of the SZ power spectrum in Ref. [11] and we illustrate the associated errors on the SZ angular power spectrum in figure 1. Note that the non-Gaussianities increase the errors associated with band power estimates by a factor of few at arcminute scales. Such an increase in the sample variance suggest that one should see a large variation in the SZ power spectrum from a field to field. This large sample variance may also explain why present day simulations of the SZ contribution, for a given cosmology, do not agree with each other to the extent expected. Given small box sizes that are currently simulated, the SZ contribution one calculates in a given simulated box varies depending on whether most massive halos have formed in that box or not. The non-Gaussianity of the SZ effect also leads to a significant three-point correlation function, or a bispectrum in Fourier space [24,10]. The measurement of such a non-Gaussianity, via collapsed statistics such as the skewness, in observed anisotropy data may aid in distinguishing the SZ contribution.

The non-Gaussianity alone, however, may not distinguish the nature of small scale anisotropy power as observed in current experiments as the non-standard modifications to the last scattering involving primordial voids also generate a highly non-Gaussian anisotropy contribution [25]. A reliable approach to distinguish between a local and an early contribution is to consider a combined study involving the large scale structure and CMB. Here, we suggest a cross-correlation of the CMB anisotropy data with a map of the large scale structure. The correlation between CMB, mainly the best COBE DMR map, and large scale structure has already been considered to understand the extent to which the ISW effect contributes at large angular scales [26]. As discussed in [27], this correlation, however, is dominated by the large cosmic variance at low multipoles corresponding to angular scales with tens of degrees on the sky. In the case of small scales anisotropies, the extent to which the correlation can be detected will be determined primarily by the instrumental noise contribution. For the purpose of this discussion, we introduce the correlation coefficient between, say, the dominant SZ effect and a tracer of the large scale structure as

$$\mathrm{Corr}(\mathrm{SZ}, i)_l = \frac{C_l^{\mathrm{SZ}-i}}{\sqrt{C_l^{\mathrm{SZ}} C_l^i}}\,, \tag{1}$$

where $C_l^{\mathrm{SZ}-i}$ is the cross power spectrum between SZ and the tracer field. These are described in Ref. [10]. The associated signal-to-noise for the detection of the cross-correlation is

$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2 = f_{\mathrm{sky}} \sum_l \frac{(2l+1)\mathrm{Corr}^2(\mathrm{SZ}, i)_l}{\mathrm{Corr}^2(\mathrm{SZ}, i)_l + \left(1 + \frac{N_l^{\mathrm{SZ}}}{C^{\mathrm{SZ}}}\right)\left(1 + \frac{N_l^i}{C_l^i}\right)}\,, \tag{2}$$

where $N_l^{\mathrm{SZ}}(= C_l^{\mathrm{CMB}} + C_l^{\mathrm{noise}})$ and N_l^i are the noise contributions to the SZ power spectrum and the power spectrum of the i tracer field. In figure 2, we show the correlation coefficient for the SZ effect and tracers of the large scale structure involving weak lensing convergence and the galaxy distribution. In the near future, a cross-correlation study of small scale anisotropies and a map of the galaxy distribution, such as from the Sloan survey, looks promising and should be considered. To calculate the expected signal-to-noise ratio for a detection of the correlation signal, we assume a noise contribution to the tracer field involving the shot-noise contribution arising from the finite number of galaxies. For a survey of 10 degrees^2 and no noise contributions, we estimate the signal-to-noise ratio of order ~ 100 while this drops to ~ 10 when reasonable noise contributions are considered to both the temperature and galaxy tracer field. For example, the galaxy shot-noise considered in this involve a surface density of 10^9 sr^{-1}, which is the density of galaxies down to a R band magnitude of 25 [28].

The extent to which small scale anisotropies correlate with large scale structure by it self does not determine the nature of the temperature fluctuation. Though it establishes that the local universe is partly responsible, a primordial void contribution can also contribute at low redshifts via the RS effect. This contribution, however, is expected to be an order of magnitude below the dominant SW contribution at one expects at the last scattering surface. Thus, any correlation between large scale structure and void RS effect is expected to be suppressed. Additionally, the RS contribution from voids is not expected to be strongly correlated with a highly non-linear tracer field such as the galaxy distribution.

In general, the extent to which SZ thermal effect contributes at small angular scales can be established more reliably based on its spectral dependence relative to thermal CMB than nay correlation associated with the large scale structure alone. The SZ frequency spectrum is unique and is unlikely to be mimicked by other sources of contributions. To determine the SZ contribution and to separate it from other thermal fluctuations at small angular scales, the future experiments should be equipped with multifrequency capabilities that expands from low RJ frequencies to ~ 300 GHz; the low frequencies help determine the radio source contribution while high frequencies determine the confusion from mid-infrared/submm point sources. The observations at SZ null of 217 GHz determine the extent to which other thermal fluctuations are significant as a source of small scale anisotropies. Though to a certain extent current and upcoming detection of small scale power may be important as a first detection, dedicated small angular scale experiments with multifrequency coverage is clearly needed to fully understand the nature of fluctuations at these small scales. Just as anisotropy studies at degree angular scales involving the acoustic peak structure have been successful as a strong probe of cosmology, the small-scale anisotropies open the window to understand both the large scale structure and important subtle effects involving the last scattering surface.

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